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May 1999

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Determining the Redshift of Reionization From the Spectra of High–Redshift Sources

Zoltán Haiman[1,2] and Abraham Loeb[1]

ABSTRACT

The redshift at which the universe was reionized is currently unknown. We examine the optimal strategy for extracting this redshift, $z_{\rm reion}$, from the spectra of early sources. For a source located at a redshift $z_{\rm s}$ beyond but close to the reionization redshift, $(1 + z_{\rm reion}) < (1 + z_{\rm s}) < \frac{32}{27}(1 + z_{\rm reion})$, the Gunn–Peterson trough splits into disjoint Lyman α, β, and possibly higher Lyman series troughs, with some transmitted flux in between these troughs. We show that although the transmitted flux is suppressed considerably by the dense Lyα forest at high–redshifts, it could still be detectable as long as $z_{\rm reion} \lesssim 8$. If the ionizing sources are bright and have a short duty–cycle (e.g. if they are mini–quasars or starbursts with a lifetime $\lesssim 10^6$ yr), then breakthrough occurs shortly after the HII regions around them overlap, and the transmitted flux provides a measurement of $z_{\rm reion}$. The Next Generation Space Telescope will reach the spectroscopic sensitivity required for such a measurement.

Subject headings: cosmology: theory – quasars: absorption lines – galaxies: formation – intergalactic medium – radiative transfer

1. Introduction

The standard Big Bang model predicts that the primeval plasma recombined and became predominantly neutral as the universe cooled below a temperature of several thousand degrees at a redshift $z \sim 10^3$ (Peebles 1968). Indeed, the recent detection of Cosmic Microwave Background (CMB) anisotropies rules out a fully ionized intergalactic medium (IGM) beyond $z \sim 300$ (Scott, Silk & White 1995). However, the lack of a Gunn–Peterson trough (GP, Gunn & Peterson 1965) in the spectra of high–redshift quasars (Schneider, Schmidt & Gunn 1991) and galaxies (Franx et al. 1997) implies that the IGM is highly ionized at low redshifts, $z \lesssim 5$. Taken together, these two observations indicate that the IGM was reionized in the redshift interval $5 \lesssim z_{\rm reion} \lesssim 300$. The epoch of reionization marks the end of the "dark ages" during which the cosmic radiation

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background was dominated by the ever-fading CMB at all wavelengths. During this epoch, ionized hydrogen (HII) started to occupy again most of the volume of the universe. Most likely, the phase transition from HI to HII was triggered by the emission from the first stars and mini–quasars in the universe (see Loeb 1998, and references therein).

The characteristic distance between the sources that ionized the universe was much smaller than the Hubble scale, and the overlap of the HII regions surrounding these sources was completed on a timescale much shorter than the Hubble time. The resulting reionization redshift, z_{reion}, is therefore sharply defined and serves as an important milestone in the thermal history of the universe. Measurement of this parameter would also constrain the small-scale power of primordial density fluctuations that produced the first objects. Theoretical models and three–dimensional simulations predict that reionization occurs at $7 \lesssim z_{\mathrm{reion}} \lesssim 20$, just beyond the horizon of current observations (Haiman & Loeb 1997, 1998; Gnedin & Ostriker 1997). Forthcoming instruments, such as the *Space Infrared Telescope Facility (SIRTF)*, and the *Next Generation Space Telescope (NGST)* are expected to reach the sensitivity required for the detection of sources beyond the reionization redshift. It is therefore timely to ask: how could one infer z_{reion} from the observed spectra of these sources?

The spectrum of a source at a redshift $z_{\mathrm{s}} > z_{\mathrm{reion}}$ should show a GP trough due to absorption by the neutral IGM at wavelengths shorter than the local Lyα resonance at the source, $\lambda_{\mathrm{obs}} < \lambda_{\alpha}(1 + z_{\mathrm{s}})$. By itself, the detection of such a trough would not uniquely establish the fact that the source is located beyond z_{reion}, since the lack of any observed flux could be equally caused by (i) ionized regions with some residual neutral fraction, (ii) individual damped Lyα absorbers, or (iii) line blanketing from lower column density Lyα forest absorbers (see, e.g. the spectrum of a $z = 5.34$ galaxy taken by Dey et al. 1998). An alternative approach proposed by Miralda-Escudé (1998) is to study the detailed shape of the damping wing of the GP trough. Although a measurement of this shape could ideally determine the optical depth of the absorbing HI slab between the source redshift and reionization, it is also likely to be compromised by contaminating effects such as: (i) redshift distortions due to peculiar velocities; (ii) uncertainties in the absorption profile due to the unknown intrinsic shape of the Lyα emission line from the source; (iii) ionization of the IGM in the vicinity of the source due to the source emission; and (iv) the existence of a damped Lyα absorber outside or inside the source.

In this paper we consider a different approach for measuring z_{reion}. Our method relies on the existence of some transmitted flux between the Lyα and Lyβ absorption troughs in the spectra of sources which are located just beyond the reionization redshift. For such sources, the GP troughs due to different Lyman series resonances do not necessarily overlap, and the transmitted flux between these troughs is only affected by the post-reionization Lyα forest. In §2, we simulate the absorption by the dense Lyα forest (or "Lyα jungle") and demonstrate that the transmitted flux features are detectable. In §3, we estimate the number of sources which are sufficiently bright to allow detection of these features with *NGST*. Finally, §4 summarizes the main conclusions of this work.

2. Spectra of High Redshift Sources

The phase transition from HI to HII occurs almost simultaneously throughout the IGM volume, when the expanding HII regions around the separate ionizing sources overlap (Arons & Wingert 1972). The expansion of spherical ionization fronts around steady sources can be calculated analytically (Shapiro & Giroux 1987). The process of overlap is nearly instantaneous (Haiman & Loeb 1998; HL98) and defines a corresponding redshift, $z_{\rm overlap}$. However, at $z_{\rm overlap}$ each individual HII region could still have a non–negligible Lyα optical depth due to its residual HI fraction (cf. Shapiro et al. 1987). The GP trough from the uniform IGM disappears only at a somewhat later redshift, $z_{\rm reion}$, when the average Lyα optical depth of the smooth IGM drops below unity (we distinguish between this GP absorption and the absorption produced due to IGM clumpiness by the post-reionization Lyα forest). In this paper, we assume that the delay between $z_{\rm overlap}$ and $z_{\rm reion}$ is small and set $z_{\rm overlap} = z_{\rm reion}$, based on the following reasoning.

The Lyα optical depth across a stationary HII sphere is as large as $\sim 10^4$ (Osterbrock 1974), but cosmological HII regions are much thinner because of the cosmological redshifting of the Lyα photons away from resonance. For concreteness, consider a case in which the HII regions are driven by mini–quasars in Cold Dark Matter halos of a virial temperature $\gtrsim 10^4$K ($M_{\rm halo} \gtrsim 1.5 \times 10^8 M_\odot$). This minimum halo size is dictated by the requirement that its gas would be able to cool efficiently via atomic transitions. With black–hole to halo mass ratios $M_{\rm bh}/M_{\rm halo} \sim 10^{-3}$ and quasar lifetimes $t_{\rm Q} \sim 10^6$ years, the typical proper radius of an HII region is $R_{\rm HII} \sim 0.05$ Mpc (see HL98 for details). The short–lived mini–quasars have a small duty–cycle, and when HII regions around two such mini–quasars first overlap, the neutral fraction at their intersection is $x \approx 2 \times 10^{-5}$ in photoionization equilibrium. Due to the short duty-cycle of the ionizing sources, the ionizing mini-quasar flux at the time of overlap is not far below the eventual flux of the cosmic UV background, integrated over a Hubble time. The resulting IGM optical depth at the time of overlap is $\tau \sim 3$. The GP trough disappears as soon as the neutral fraction is reduced by another factor of ~ 3, i.e. when the local UV flux is increased by this factor. Such an increase could occur shortly after the overlap epoch, since it requires the cumulative contribution from only a few additional sources. To encounter a sufficient number of already existing active sources, the required radius is $\sim 100 \times 3 \times 0.05$ Mpc $= 15$ Mpc (where the factor of ~ 100 is the inverse of the duty–cycle). The light-crossing time across this radius causes a short ($\sim 5\%$) delay for the breakthrough redshift, $z_{\rm reion}$, relative to the overlap redshift, with $(z_{\rm overlap} - z_{\rm reion}) \approx 0.4$ in this case. Note, however, that clustering of the ionizing sources, or appearance of new active sources on a timescale significantly shorter than the local Hubble time can shorten this redshift delay. On the other hand, if the ionizing sources have a significantly longer lifetime than we assumed (e.g. long-lived star forming galaxies) then reionization would be more gradual, as outlined by Miralda-Escudé (1998). We illustrate this possibility in Figure 4 below. In this case, we point out that the Lyβ optical depth is ~ 3.5 times below that of Lyα, so that the Lyβ and higher GP troughs are more sharply defined than the Lyα trough for gradual reionization.

We now consider the spectrum of a source located at a redshift $z_{\rm s} > z_{\rm reion}$. Ly$\alpha$ absorption

by neutral hydrogen between z_{reion} and z_{s} suppresses the flux in the observed wavelength interval, $(1 + z_{\mathrm{reion}})\lambda_\alpha < \lambda_{\mathrm{obs}} < (1 + z_{\mathrm{s}})\lambda_\alpha$; Ly$\beta$ absorption causes a second trough at $(1 + z_{\mathrm{reion}})\lambda_\beta < \lambda_{\mathrm{obs}} < (1 + z_{\mathrm{s}})\lambda_\beta$, and higher Lyman series lines produce analogous troughs at shorter wavelengths. In the absence of other effects, the resulting spectrum would consist of a generic sequence of troughs separated by blocks of transmitted flux, as depicted in Figure 1. In this illustration we assumed that reionization occured suddenly as discussed above, at $z_{\mathrm{reion}} = 7$, but included the damping wings of the Lyman lines at both edges of the absorption troughs (see the Appendix in Miralda-Escudé 1998). Note that a Lyα photon emitted by the source can escape from its host's HII region and travel across the uniform IGM only if the HII region has an unusually large radius of at least ~ 1 Mpc. The emitted Lyα photons are much more likely to be absorbed by the IGM. Below we consider observations on a telescope with a sufficiently high angular resolution, so that the diffuse Lyα re-emission by the IGM can be ignored.

The top panel of Figure 1 shows that the closer z_{s} gets to z_{reion}, the narrower the GP troughs become and the more similar they look to individual Lyα absorbers. Equation (1) below predicts a few damped Lyα systems with neutral hydrogen column densities $N_{\mathrm{H}} \gtrsim 10^{20}$ cm^{-2} in the spectra of a source at redshifts $z_{\mathrm{s}} \gtrsim 5$. A single absorber with $N_{\mathrm{H}} = 10^{20}$ cm^{-2} and $b = 35$ km s^{-1} would have a rest–frame equivalent width of 7.7Å. In order to avoid confusion with such an absorber, the width of the GP troughs must be $\gtrsim 8(1 + z_{\mathrm{s}})$Å. Note also that peculiar velocities could shift the location of the narrow troughs by ~ 10Å. The bottom panel of Figure 1 also indicates that as the source redshift approaches the limiting value $(1 + z_{\mathrm{s}})/(1 + z_{\mathrm{reion}}) = \lambda_\beta/\lambda_\alpha = 32/27$, only a single narrow block of transmitted flux remains between the Lyα and Lyβ troughs. At still higher redshifts this window disappears, leaving a continuous GP trough at wavelengths $\lambda_{\mathrm{obs}} < \lambda_\alpha(1 + z_{\mathrm{reion}})$ which carries no information about the reionization redshift.

Reionization also leaves a distinct mark in the soft X-ray regime. The source spectrum would be strongly suppressed at the Lyman edge, $\lambda_{\mathrm{obs}} = 912(1 + z_{\mathrm{s}})$Å, due to the large continuum optical depth in from H and He ionizations ($\tau_{\mathrm{cont}} \sim 10^5$). The optical depth drops at shorter wavelengths due to the sharp decline in the ionization cross–sections, $\sigma \propto \lambda^3$. The flux recovers its intrinsic amplitude at $E \gtrsim 0.1$ keV, where the optical depth falls below unity. The observed photon energy where this occurs provides a measure of the reionization redshift, as long as the value of $\Omega_{\mathrm{b}} h^2$ is independently measured. Note that the hydrogen GP signal could be contaminated by absorption from intervening Lyman limit and damped Ly α systems, the equivalent tail of the HeII GP trough, and galactic foreground absorption (O'Flaherty & Jakobsen 1997). Ignoring these issues, it is interesting to ask whether $AXAF$ would be able to detect the spectral signature in the ideal case. For a source whose observed flux at $E = 0.1$ keV is 100 nJy, the $AXAF$ count rate in the 0.08-0.15 keV band would be 10^{-3} per second[3], sufficiently large to collect 100 photons in 10^5 seconds. The ability of $AXAF$ to determine z_{reion} relies on the existence of sufficiently bright sources beyond

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[3]We consider detection by the High Resolution Camera and the Low Energy Transmission Grating, based on the proposal planning toolkit at http://asc.harvard.edu/cgi-bin/prop_toolkit.cgi.

the reionization redshift. In the case where these sources are early mini–quasars, their required infrared flux is $\gtrsim 10\mu$Jy. As illustrated by Figure 6 below, such sources are expected to be very rare at $z > 5$.

The spectra shown in Figure 1 are highly idealized in that they take account only of absorption by the homogeneous HI gas between z_s and z_{reion}. In reality, the blocks of transmitted flux shown in Figure 1 will be suppressed due to absorption by the residual HI islands in the clumped IGM which produce the Lyα forest after reionization. In order to simulate the effect of the dense Lyα forest (or "Lyα jungle"), we created mock catalogs of absorption lines with statistical properties constrained by observational data at $z < 5$. Fardal, Giroux & Shull (1998) have recently analyzed in detail the statistics of Lyα absorbers observed between redshifts $1.5 < z < 4.5$. Using a maximum likelihood method, they obtained the mean number $n(N_{\text{H}}, b, z) dN_{\text{H}} db dz$ of clouds with HI column density between N_{H} and $N_{\text{H}} + dN_{\text{H}}$, Doppler velocity parameter between b and $b + db$, and redshift between z and $z + dz$. In their procedure, the Doppler parameter b and column density N_{H} is obtained for each absorber by Voigt profile fitting. Their resulting best fit for $n(N_{\text{H}}, b, z)$ is a 4–segment broken power–law in N_{H}, where each segment is valid for a different range of values for N_{H}, and has the form

$$n(N_{\text{H}}, b, z) = A(1 + z)^{\gamma} \left(\frac{N_{\text{H}}}{10^{17} \text{ cm}^{-2}} \right)^{-\beta} p(b) \quad \text{cm}^2 \text{ km}^{-1} \text{ s}, \tag{1}$$

with

$$p(b) \propto \exp\left[-\frac{(b - b_0)^2}{2b_*^2} \right] \quad (b > 20 \text{ km s}^{-1}) \tag{2}$$

and $\int_0^\infty p(b) db = 1$, $b_0 = 28$ km s^{-1}, and $b_* = 10$ km s^{-1}. The best–fit values of A, β, and γ for each of the 4 segments are summarized by Fardal, Giroux & Shull (1998). We used a Monte Carlo approach to generate a catalog of absorbers along the line of sight to the source, with redshifts, column densities, and b–parameters in the ranges $0 \le z_i \le z_{\text{reion}}$; 2×10^{12} cm$^{-2} \le N_{\text{H},i} \le 10^{20}$ cm^{-2}; and $b_i \ge 0$, for $1 \le i \le N_{\text{abs}} = \int n \, dz \, dN_{\text{H}} db$. The probability distribution of these parameters was chosen according to the above equations. Although these equation are based on data from redshifts $1.5 < z < 4.5$, in the absence of additional data at higher z, we extend their validity to all redshifts below z_{reion}. A more rigorous extrapolation of this equation to high redshift would be to use three-dimensional numerical simulations of the high–redshift IGM (e.g., Hernquist et al. 1996). However, even such a calculation would be highly uncertain due to the unknown evolution of the flux and spectrum of the UV background at $z > 5$.

In computing the observed flux F from the source at a wavelength λ_{obs} we include absorption by the first nine Lyman series lines from each of the $N_{\text{abs}}(z_{\text{reion}})$ absorbers along the line of sight,

$$F(\lambda_{\text{obs}}) = F_0 \prod_{n \in [1,9]} \prod_{i \in [1,N_{\text{abs}}]} e^{-\tau_{i,n} U(x_{i,n}, a_{i,n})}. \tag{3}$$

Here F_0 is the continuum flux that would have been observed in the absence of Lyα absorbers; $\tau_{i,n} = (\pi e^2 / m_e c) N_{\text{H},i} \lambda_n f_n / b_i$ is the integrated optical depth for the n$^{\text{th}}$ Lyman line of the i$^{\text{th}}$

absorber; and λ_n and f_n are the rest wavelength and oscillator strength of this line. The profile of each line is given by the normalized Voigt function $U(x,a)$, where $x_{i,n} \equiv (c/b_i)[\lambda_{obs}/(1+z_i) - \lambda_n]/\lambda_n$; $a_{i,n} \equiv \Gamma_n \lambda_n / 4\pi b_i$; and Γ_n is the natural decay rate of the nth Lyman line (see Press & Rybicki 1993 for more details).

Figure 2 shows five examples of source spectra processed through the mock Lyα jungle. As in Figure 1, we assume sudden reionization at $z_{reion} = 7$ but include the damping wings of the GP troughs. The several thousand absorbers along a typical line of sight yield a considerable mean optical depth, $\tau \approx 3.4$. Although the underlying continuum flux is not visible at any wavelength, the figure reveals a series of narrow features of transmitted flux – remnants of the processing by the underlying Lyα jungle – to which we refer hereafter as "transmission features". The spectra contain many such features with central flux values that rise infrequently up to a significant fraction (up to $\sim 50\%$) of the original continuum flux. These features could be detected by an instrument with a sufficiently high sensitivity and spectral resolution.

As an example, we show in Figure 3 a blow–up of the spectrum around the Ly α and β GP troughs of a source with a redshift $z_s = 7.08$. The spectrum indeed contains numerous transmission features; these features are typically a few Å wide, have a central intensity of a few percent of the underlying continuum, and are separated by ~ 5Å. With a sensitivity reaching 1% of the continuum, the edges of the Lyβ GP trough between 8201 and 8283 Å could be identified to a ~ 5 Å accuracy. A similar precision applies to the Lyα GP trough, although the damping wing there suppresses the flux within ~ 10 Å of the edges by a factor of ~ 3. The longest wavelength at which flux is detected towards the blue edge of the Lyβ GP trough, at ~ 8201 Å, provides the best direct measurement of the reionization redshift. In practice, this method only yields a lower limit to z_{reion}, since the first observed transmission feature could be offset from the true blue edge of the GP trough. The uncertainty in the measurement of $\lambda_\beta(1 + z_{reion})$ would be equal to the typical separation between the transmission features. Figure 3 shows that at a sensitivity reaching 1% of the continuum, the separation would be small (~ 5Å), leading to a fractional error of only $\sim 5/8200 \sim 0.1\%$ in the measurement of z_{reion}. Note that this accuracy is similar to the level allowed by peculiar velocities of a few hundred km/s, which could move either observed edge of the GP trough by ~ 10Å.

It is apparent from Figure 3 that the above procedure applies only as long as the typical separation between the transmission features is much smaller than the width of the GP trough, i.e. for $(1 + z_s) \gtrsim 1.01 \times (1 + z_{reion})$. The bottom three panels in Figure 2 also show that the transmission features gradually disappear as the GP troughs of the Lyα and Lyβ resonances approach overlap at $(1 + z_s)/(1 + z_{reion}) = \lambda_\alpha/\lambda_\beta = 32/27$. Hence, suitable sources must lie in the somewhat more restricted redshift range, $1.01 \lesssim (1 + z_s)/(1 + z_{reion}) \lesssim 1.17$. Finally, we note that an extrapolation of equation (1) to even higher redshifts predicts that the mean optical depth of the Lyα clouds increases strongly with redshift. For example, using our mock Lyα cloud catalog, we find that at wavelengths just below $\lambda_\alpha(1 + z_{reion})$, the mean optical depth increases from $\tau = 3.4$ for $z_{reion} = 7$ to $\tau = 10.4$ for $z_{reion} = 10$. Similar numbers ($\sim 30\%$ higher optical depths for

a less accurate description of the Ly α forest) are obtained by extrapolating the expressions for the mean optical depth from Madau (1995). This implies that detection of the remnant transmission features is considerably more difficult at higher redshifts, since the number density of lines above a given sensitivity threshold drops as $\sim \exp(-\tau)$. In order to detect transmission features separated by roughly ~ 10Å, as in Figure 3, the spectroscopic sensitivity must reach the approximate fractions of $\sim 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}$, and 10^{-6} of the continuum flux for $z_{\rm reion} = 6, 7, 8, 9$, and 10, respectively.

Finally, we illustrate the possibility of a more gradual reionization process in Figure 4. Rather than assuming abrupt reionization at $z_{\rm overlap} = z_{\rm reion} = 7$, we assume that after the sudden overlap of HII regions at $z_{\rm overlap} = 7$, the neutral fraction within the IGM is still non-negligible, $x = 10^{-4}$. We assume further that the cosmic background flux J increases linearly in time by a factor of 100 between $z = 7$ and $z = 6$, so that the neutral fraction drops (as $1/J$) to $x = 10^{-6}$ by $z = 6$. To be consistent with this evolution of J, we also assume that the neutral column density of each Ly α cloud with $N_{\rm H} < 10^{17}$ cm^{-2} (i.e. those clouds that are not self–shielding) evolves as $1/J$ between $z = 6$ and $z = 7$. As Figure 4 demonstrates, the flux is suppressed by several orders of magnitude at the blue side of the GP troughs, and recovers its sudden–reionization value only several hundreds of Å away from the edge of the trough. Under these conditions, a measurement of the frequency where the flux appears at the blue side of the Lyβ GP trough would yield a value $z \sim 6.8$, which is lower than the overlap redshift $z_{\rm overlap} = 7$. The redshift inferred from the Lyα trough would be still slightly lower, $z \sim 6.6$.

3. Abundance of Suitable High Redshift Sources

The detection of a single bright source from the epoch, $1.01(1 + z_{\rm reion}) < (1 + z_{\rm s}) < 1.17(1 + z_{\rm reion})$, could in principle provide an unambiguous measurement of $z_{\rm reion}$. How likely is it to find such sources? The best candidates are high–redshift mini–quasars, since in analogy with their $z < 5$ counterparts, they are expected to have a hard spectrum extending into the far UV. Alternative sources are Gamma-Ray Burst (GRB) afterglows, supernovae, or primeval galaxies. The advantage of GRB afterglows is that they are bright and have featureless power–law spectra; however, their abundance at high redshifts might be small. Supernovae and galaxies may be more abundant than either mini–quasars or GRBs, but are likely to be faint and possess soft spectra in the relevant UV range (see, e.g. two recent detections of candidate galaxies at redshifts z=5.64 [Hu et al. 1998]; and $z = 5.60$ [Weymann et al. 1998]).

As the abundance of mini–quasars at $z > 5$ is currently unknown, we must resort to an extrapolation of the observed luminosity function (LF) of quasars at $z \lesssim 5$. Such an extrapolation has been carried out by HL98 using a simple model based on the Press–Schechter (1974) formalism. In the model of HL98, the evolution of the quasar LF at faint luminosities and high redshifts is derived from three assumptions: (i) the formation of dark–matter halos follows the Press–Schechter theory, (ii) each dark halo forms a central black hole with the same efficiency, and (iii) the

light–curve of all quasars, in Eddington units, is a universal function of time. As shown in HL98, these assumptions provide an excellent fit to the observed quasar LF at redshifts $2.6 < z < 4.5$ for an exponentially decaying lightcurve with a time–constant of $\sim 10^6$ years. The model provides a simple and natural extrapolation of the quasar LF to high redshifts and faint luminosities. At the faint end of the LF, the number counts of mini–quasars are expected to be reduced because of feedback due to photoionization heating that prevents gas from reaching the central regions of shallow potential wells. To be consistent with the lack of faint point–sources in the Hubble Deep Field, we imposed a lower limit of ~ 75 km s^{-1} for the circular velocities of halos harboring central black holes (Haiman, Madau & Loeb 1998). Figure 5 shows the resulting number counts of mini–quasars, from redshifts above $z = 5$ and $z = 10$, as a function of the threshold flux in the 1–3.5 μm wavelength range of NGST. For reference, this figure also shows the expected number of high–redshift star–clusters in a similar model, in which the star formation efficiency is calibrated to the observed IGM metallicity ($10^{-3}Z_\odot \lesssim Z \lesssim 10^{-2}Z_\odot$, see Songaila 1997) at $z \sim 3$.

Figure 6 shows the total number $N(z, F)$ of mini–quasars brighter than the minimum flux F, that are located within the suitable redshift interval, $1.01(1 + z) < (1 + z_s) < 1.17(1 + z)$, in a $16' \times 16'$ field (16 times the field of view of NGST). How many suitable sources would NGST detect? For $z_{\rm reion} = 7$, the average transmitted flux shortward of the Lyman α and β GP troughs is a fraction $\exp(-\tau) \approx 1\%$ of the continuum. Around $z \sim 7$, we expect roughly a single $\sim 10^3$ nJy source per $16' \times 16'$ field, based on Figure 6. Such a source has an average flux of $\sim$10 nJy blueward of $\lambda_\alpha(1 + z_s)$ due to absorption by the Lyα jungle. According to the method depicted on Figure 3, a determination of $z_{\rm reion}$ to $\sim 1\%$ accuracy would require spectroscopy with a resolution of R=100. Requiring a signal-to-noise of S/N=10, the necessary integration time for a 10 nJy source with NGST would be roughly 10 hours[4]. This is a conservative estimate for the detection of flux, since it assumes that the flux is uniformly distributed across the spectrum, while in reality it would be concentrated in transmission features that cover narrow wavelength bins and yield a higher S/N ratio in these bins. We therefore conclude that NGST will be able to measure the reionization redshift to $\sim 1\%$ percent accuracy up to $z_{\rm reion} = 7$. The accuracy would degrade considerably with redshift for $z_{\rm reion} \gtrsim 7$.

The total number of sources per $16' \times 16'$ field, irrespective of their redshifts, is $\sim 3 \times 10^3$, ~ 600, and ~ 90 for a minimum intrinsic flux of F_0=10, 100, and 1000 nJy, respectively. In the most optimistic case, for which the reionization redshift is close to the peak of the relevant curve in Figure 6, up to $\sim 25\%$ of all detected sources in each image would lie in the redshift range $1.01(1 + z) < (1 + z_s) < 1.17(1 + z)$, and reveal the features depicted in Figure 2. However, since only a small fraction of all baryons need to be incorporated in collapsed objects in order to ionize the IGM, reionization is likely to occur before the redshift at which the source number-count peaks ($z_{\rm peak} = 3.5, 4.5$, or 6 at sensitivities of $10^3, 10^2$, or 10 nJy). Pre–selection of sources in

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[4]This result was obtained using the NGST Exposure Time Calculator, available at http://augusta.stsci.edu. We assumed a mirror diameter of 8m, and adopted the shortest wavelength currently available, $\lambda = 1\mu$m.

particular redshift bins could be achieved photometrically by bracketing the associated location of their Lyα troughs with two narrow-band filters.

4. Conclusions

We have shown that the Gunn–Peterson effect breaks into individual Lyman series troughs in the spectra of sources located in the redshift interval $1 < (1 + z_{\rm s})/(1 + z_{\rm reion}) < 32/27$. Although the transmitted flux in between these troughs is heavily absorbed by the Lyα jungle after reionization, the residual features it shows allow a determination of the reionization redshift, $z_{\rm reion}$, for sufficiently bright sources. For a single source, a reionization redshift $z_{\rm reion} \sim 7$ could be determined to a precision of $\sim 1\%$ with a spectroscopic sensitivity of $\sim 1\%$ of the continuum flux. A simple model for the abundance of high–redshift mini–quasars predicts that a single source per $16' \times 16'$ field could allow this detection at the ~ 10 nJy spectroscopic sensitivity of *NGST*. It may also be feasible to probe reionization with ground–based telescopes. Using the Keck telescope, Dey et al. (1998) have recently detected a source at z=5.34, and found no continuum emission below the rest–frame Lyα wavelength. The authors were able to infer a lower limit of $\tau = 1.2$ on the optical depth of the Lyα forest between 1050 and 1170 Å to z=5.34, which falls just short of the $1.3 < \tau < 1.9$ implied by equation (1) for this redshift and wavelength range. Therefore, a somewhat more sensitive spectrum of this object could potentially constrain reionization at $z < 5.34$.

The signal-to-noise ratio in the determination of $z_{\rm reion}$ might be improved by co–adding the spectra of several sources. In the absence of Lyα jungle absorption, the cumulative spectrum would approach the sawtooth template spectrum derived by Haiman, Rees, & Loeb (1998, Fig. 1) and would be isotropic across the sky. An alternative signature of reionization should appear at the soft X-ray region of the spectrum ($E \approx 0.1$ keV), where the continuum optical depth to H and He ionization drops below unity. *AXAF* could detect such a signature in the spectra of only exceptionally bright objects.

In order to enable a measurement of $z_{\rm reion}$ at redshifts as low as 6, it is essential that the wavelength coverage of *NGST* would extend down to $\sim 7\lambda_\beta = 0.7\mu$m. Detection of the transmitted flux features requires progressively higher sensitivities as $z_{\rm reion}$ increases because of the likely increase in the optical depth of the Lyα jungle with redshift. For sudden reionization, the nominal integration time of about 10 hours for a ~ 10 nJy sensitivity (with R=100 and S/N=10) would be sufficient to determine $z_{\rm reion}$ up to a redshift of ~ 7 with a precision of several percent. More gradual reionization would smear the edge of the GP trough. Following the extrapolation of equation (1) to higher redshifts, the required sensitivity needs to be one or two orders of magnitude higher if $z_{\rm reion} \sim 8$ or ~ 9. Note, however, that if $z_{\rm reion} \gtrsim 10$, then it will be more easily measurable through the damping of the CMB anisotropies on small angular scales (HL98). Near the planned spectroscopic sensitivity of *NGST*, most sources are expected to have redshifts lower than $z_{\rm reion}$. However, suitable high-redshift sources could be pre-selected photometrically in analogy with the

UV dropout technique (Steidel et al 1996), by searching for the expected drop in the flux at the blue edge ($\lambda_\alpha[1 + z_{\mathrm{reion}}]$) of the Ly$\alpha$ GP trough.

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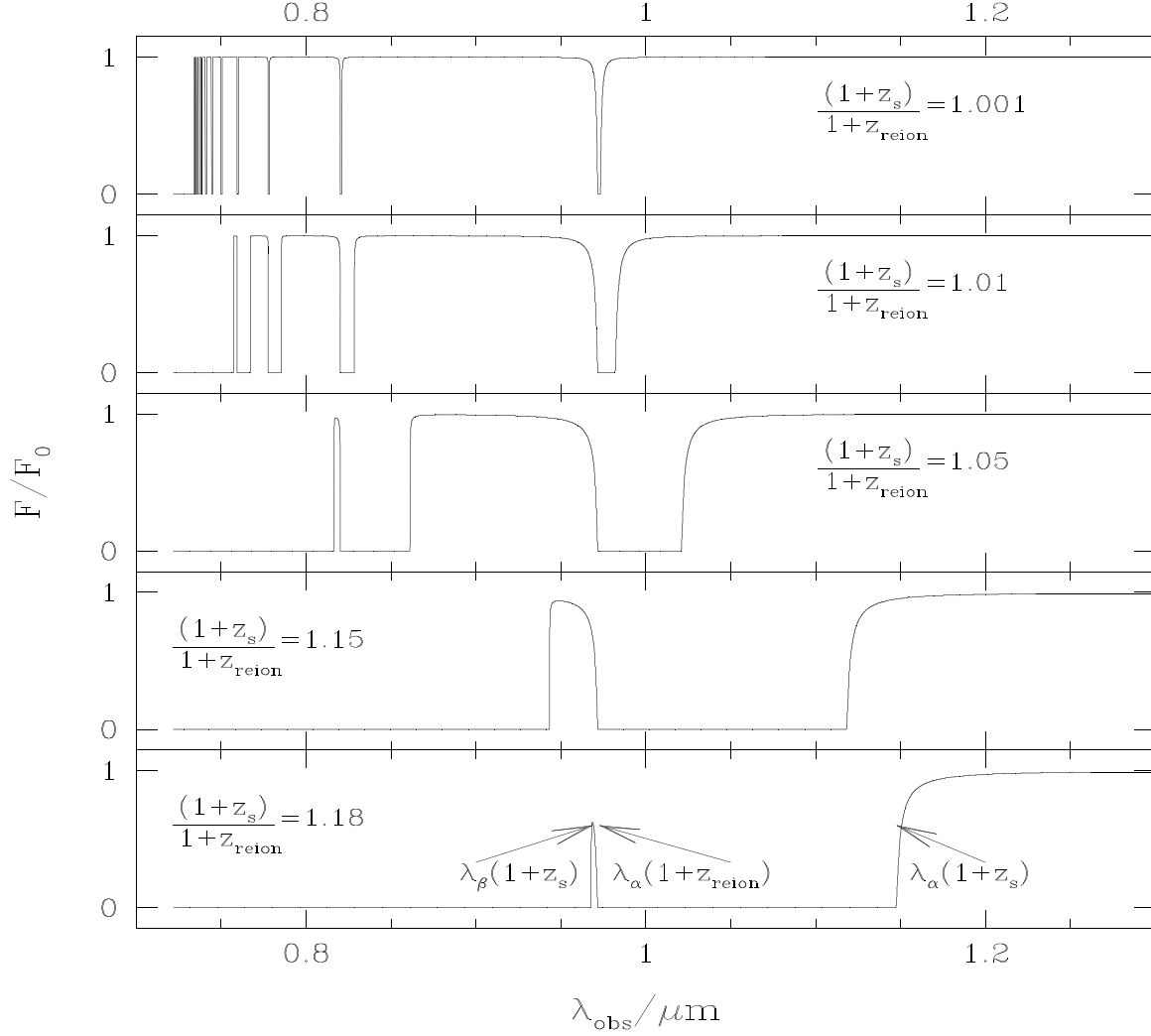
Fig. 1.— Spectra of five sources located beyond the reionization redshift (here taken to be $z_{\rm reion} = 7$), when all contaminating effects, such as peculiar velocities, the ionization of the IGM in the vicinity of the source, or absorption by the Lyα forest, are ignored.
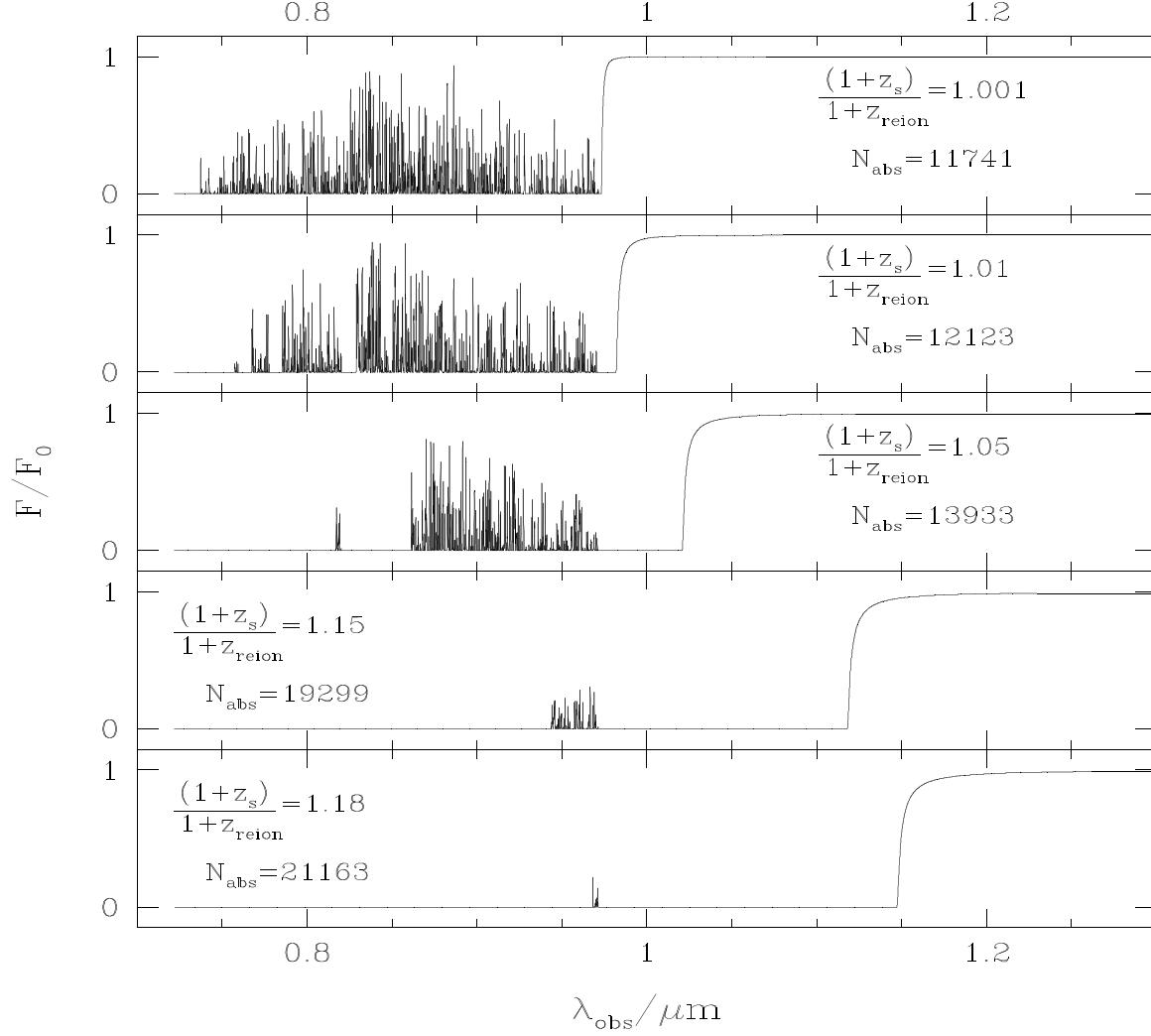
Fig. 2.— Spectra of the five sources in Figure 1, when the absorption due to the post-reionization Lyα forest is taken into account.
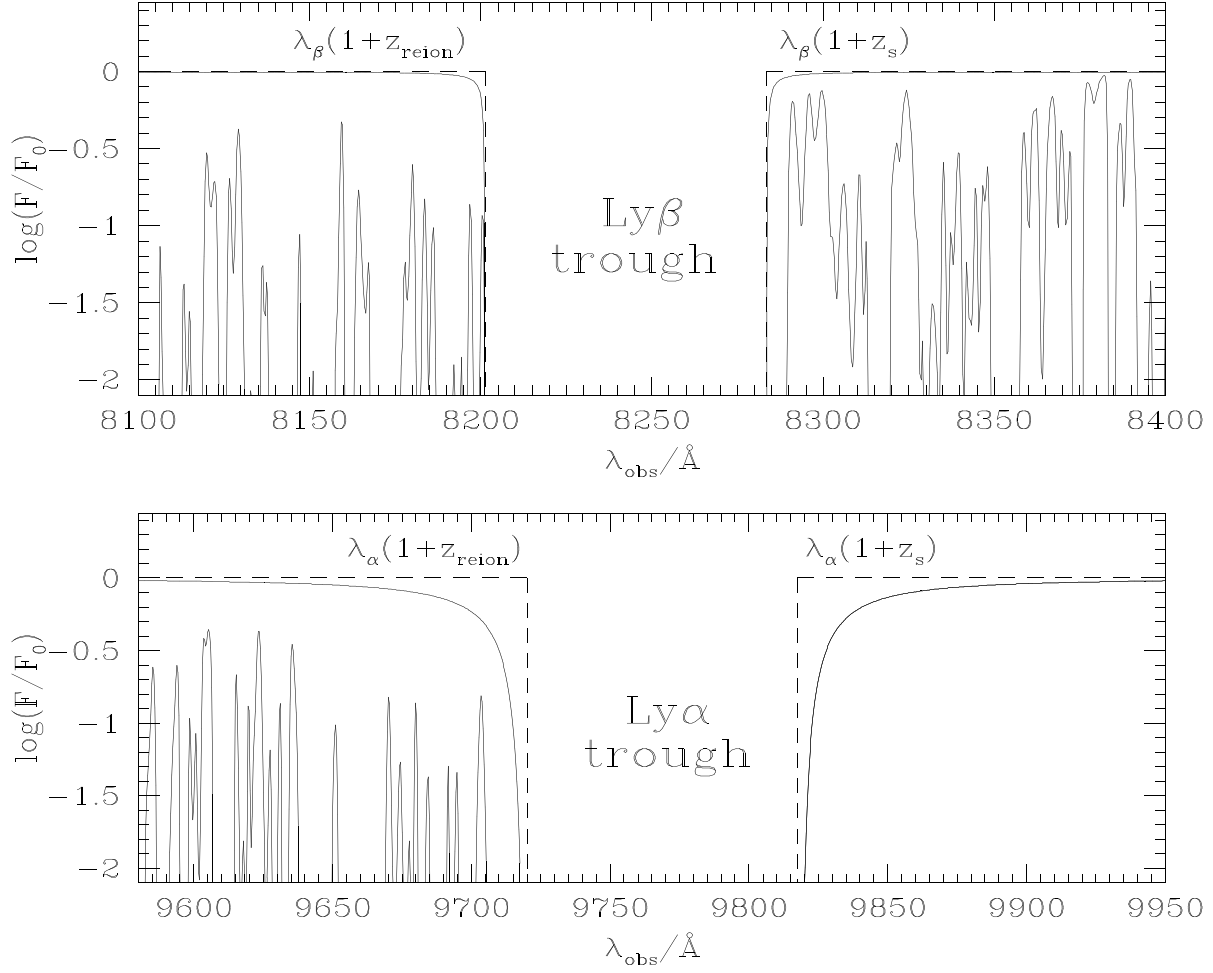
Fig. 3.— Blow–up of the spectrum of a source at $z_{\rm s} = 7.08$, assuming sudden reionization at a redshift $z_{\rm reion} = 7$. The solid curves show the spectrum without absorption by the high–redshift Lyα forest, and the dashed lines show the spectrum when the damping wings are also ignored.
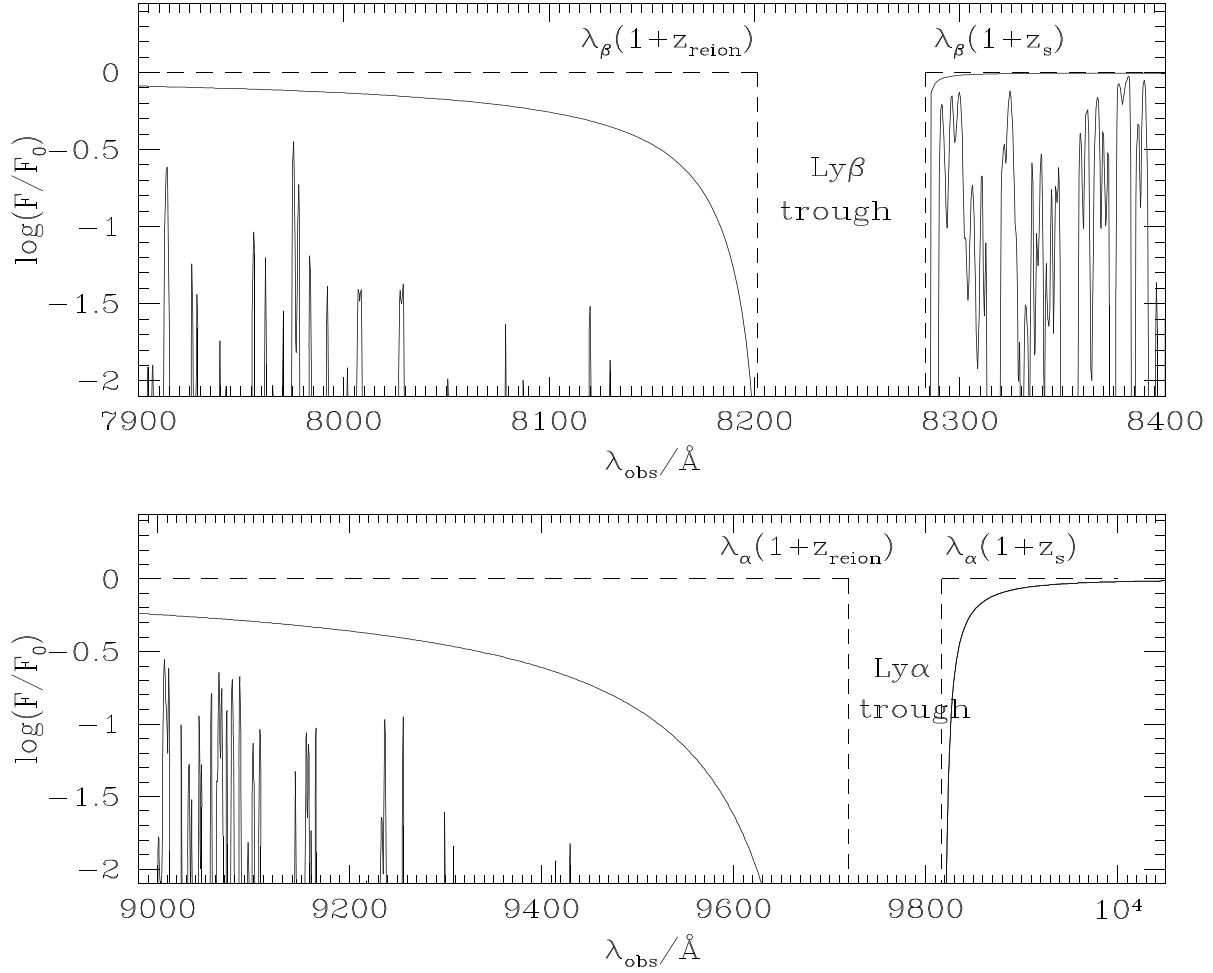
Fig. 4.— Same as Fig. 3, but assuming that the cosmic flux J builds up linearly in time between $z = 7$ and $z = 6$, and the neutral fraction decreases as $1/J$ from 10^{-4} to 10^{-6} during this redshift interval.
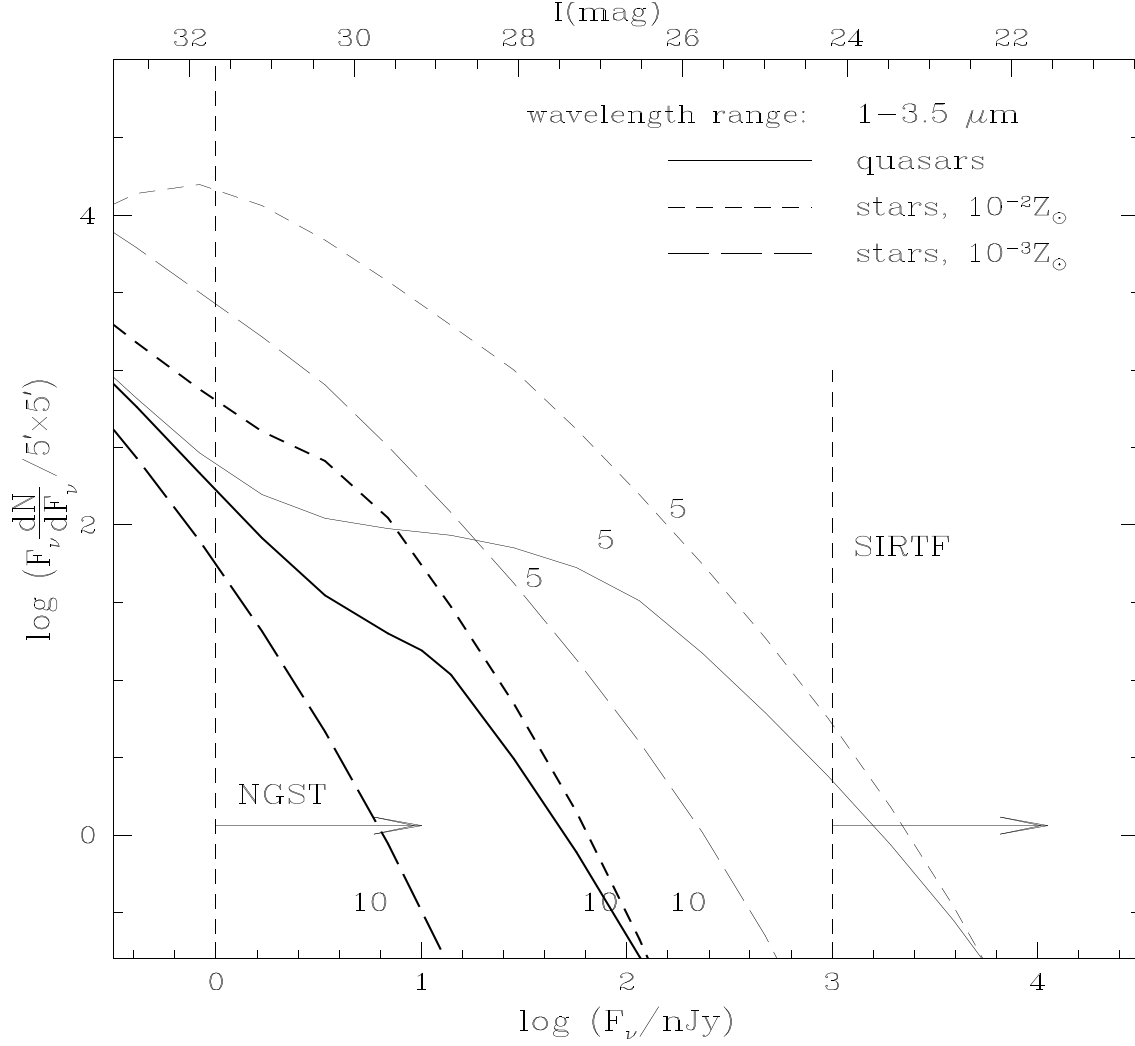
Fig. 5.— Predicted number per logarithmic flux interval of high–redshift objects which could be probed by the future space telescopes SIRTF and NGST, in the wavelength range of 1–3.5μm. The observed quasar luminosity function was extrapolated to high redshifts using the model in HL98, and the star formation efficiency was calibrated to the observed IGM metallicity ($10^{-3}Z_{\odot} \lesssim Z \lesssim 10^{-2}Z_{\odot}$) at redshift $z \sim 3$.
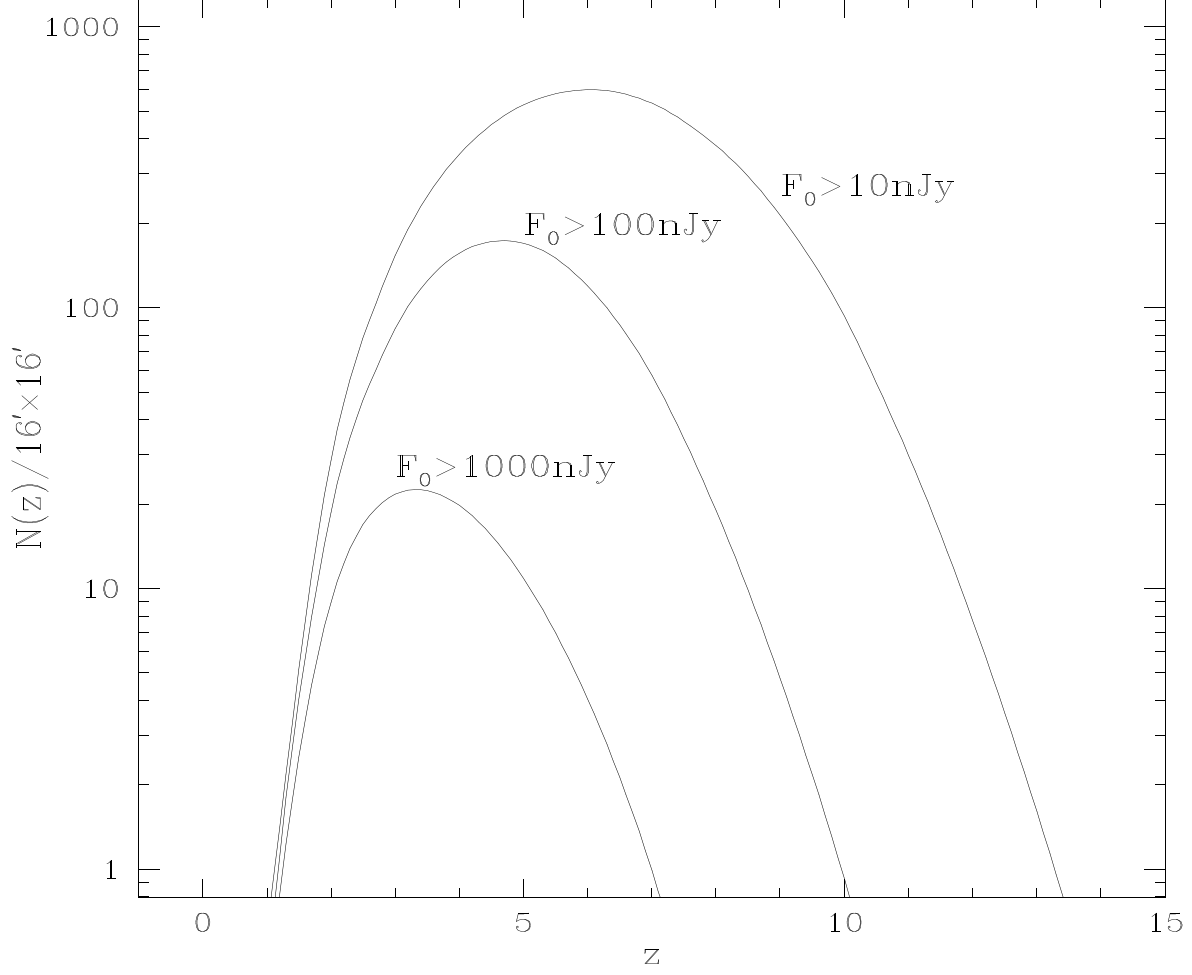
Fig. 6.— Predicted number of mini–quasars within the redshift interval $1.01(1 + z) < (1 + z_s) < 1.17(1 + z)$, with a minimum intrinsic flux F_0, in a $16' \times 16'$ field (sixteen $4' \times 4'$ *NGST* fields of view). The observed quasar luminosity function was extrapolated to high redshifts using the model in HL98.